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## Massive Star Birth in the Inner Galaxy: Obscured Massive Star Clusters

Robert D. Blum

*Cerro Tololo Interamerican Observatory, Casilla 603, La Serena, Chile,  
rblum@noao.edu*

Peter S. Conti

*JILA, University of Colorado, Campus Box 440, Boulder, CO, 80309,  
pconti@jila.colorado.edu*

Augusto Damineli & Elysandra Figuerêdo

*IAG-USP, Av. Miguel Stefano 4200, 04301-904, São Paulo, Brazil,  
daminel@iagusp.usp.br*

### Abstract.

The current census of, and stellar population in, massive Galactic star clusters is reviewed. In particular, we concentrate on a recent survey of obscured Galactic Giant H II (GHII) regions and the associated stellar clusters embedded in them. The regions have been selected as the most luminous radio continuum sources, and as such the stellar clusters appear to be among the youngest massive clusters in the Galaxy. The emergent stellar populations are further studied through near infrared spectroscopy of the brighter members. We also discuss the massive stellar clusters within 50 pc of the Galactic center (GC), comparing their known properties to those found in the GHII region survey. It is suggested that the somewhat younger clusters associated with the GHII regions are more suited to measuring the initial mass function in massive star clusters. Narrow band images in the central pc of the GC are presented which identify the young stellar sequence associated with the evolved He I emission line stars.

## 1. Introduction

Near infrared (1–2.5  $\mu\text{m}$ ) spectroscopic classification techniques have recently been developed for OB stars (Hanson, Conti, & Rieke 1996; Blum et al. 1997, Hanson, Rieke, & Luhman 1998) and Wolf-Rayet (WR) stars (e.g., Eenens, Williams, & Wade 1991; Figer, McLean, & Morris 1997). Coupled with infrared spectrometers on large telescopes, these classification schemes are now pushing forward the exploration of optically obscured, young stellar populations throughout the inner Galaxy. Propelled by the pioneering work of Hanson, Howarth, & Conti (1997) who presented a detailed investigation of the ionizing O and B stars in M17, we have carried out a survey of Galactic giant H II (GHII) regions

(Blum, Conti, & Damineli 1999, Blum, Damineli, & Conti 2000, Blum, Conti, & Damineli 2001, Figuerêdo 2001, Figuerêdo et al. 2002, Conti & Blum 2002*a, b*). As summarized below, these near infrared studies are producing a wealth of new information on the embedded stellar content in GHII regions including the discovery of young stellar objects (YSO), massive star formation processes, and new distance determinations through spectroscopic parallaxes. For the purposes of this review, we take the term YSO to include hydrogen burning objects buried in ultra-compact H II (UCHII) regions.

While this work has concentrated on GHII regions, great progress is also being made on investigating the central stars of compact and ultra-compact H II regions (Watson & Hanson 1997, Henning et al. 2001, Kaper 2002) using similar techniques. As shown in the next sections, the GHII region sample is aimed at investigating star formation in the most massive clusters where the presence of multiple O stars may affect both the process and resultant mass function. The nearby Orion star forming region is then seen as a transition object between regions of lower mass star formation and higher mass star formation. We can expect the great body of work established in Orion (e.g. Zinnecker et al. 1993, McCaughrean et al. 1994, Hillenbrand 1997, Hillenbrand & Carpenter 2000) on the mass function there to provide an important reference point to the GHII region investigations.

The young stellar content in the Galactic center (GC) has also been intensely studied at near infrared wavelengths. It has been revealed that the stellar cluster in the central parsec, as well as two other nearby clusters, are rich in OB and Wolf-Rayet stars (see Morris & Serabyn 1996 for a recent review). We will discuss below several aspects of massive stars in the GC which have been the subject of recent large telescope studies.

## 2. Giant H II Regions

Our sample of GHII regions includes all objects in the list of Smith, Mezger, & Biermann (1978) for which the Lyman continuum output indicates multiple O stars are present ( $> 10 \times 10^{49} \text{ sec}^{-1}$ ). The target GHII Regions are shown in Table 1. Where available, literature references are given for each region.

Near infrared imaging has revealed dense, rich clusters of new born stars in nearly all of the GHII regions listed in Table 1. Figure 1 shows a representative subset of the clusters imaged to date. The majority show a combination of complex nebular emission, regions of high and variable extinction, and centrally concentrated clusters of stars. A notable exception is W49. Only ultra-compact H II regions are seen toward the core of W49, with several near infrared counterparts. W49 is discussed at length by Conti & Blum 2002*a, b*. Figure 1 may be thought of as a rough “evolutionary” sequence in the sense that the GHII regions to the upper left (W33, G333.6-0.2) are still very much embedded and so probably younger. The near infrared point sources are still highly veiled by the hot dust from their birth cocoons that no photospheric features have been detected in the candidate O stars. To the lower right (e.g. W43) the clusters have become more revealed and individual stars have well determined spectral types. The brightest object in W43 is a Wolf-Rayet type star (WN7) which suggests an age  $\gtrsim 2$  Myr (Blum et al. 1999). Intermediate clusters such as W42

Table 1. Giant H II Regions from Smith et al. (1978)

Name	Radio Name	Distance (kpc) <sup>a</sup>	N LyC (10 <sup>49</sup> ) <sup>a</sup>	Notes <sup>b</sup>
RCW49	G284.3-0.3	6	96	*
NGC3576	G291.3-0.7	3.6	26	Figuerêdo 2001, *
NGC3603	G291.6-0.5	8.2	188	Brandl et al. 1999, Eisenhauer et al. 1998
-	G298.2-0.3	11.7	61	*
-	G298.9-0.4	11.5	57	
-	G305.2+0.2	8:	49	
-	G305.4+0.2	8	43	
-	G316.8-0.1	12.1	80	
-	G331.5-0.1	11.1	100	
-	G333.0-0.4	13.6:	156	*
-	G333.1-0.4	13.4	169	*
-	G333.6-0.2	14.1	1140	*
-	G336.8-0.0	12.4	192	
-	G338.4+0.0	15.3:	208	
RCW122	G348.7-1.0	>4.5	14	
-	G351.6-1.3	>4.5	11	*
SgrA	G0.5-0.0	10	132	
SgrB	G0.7-0.0	10	308	
W31	G10.2-0.3	5.1:	30	Blum et al. (2001), *
W33	G12.8-0.2	4.6	5	*
M17	G15.1-0.7	2.3	54	Hanson et al. (1997)
-	G20.7-0.1	18.8	42	
W41	G22.8-0.3	12.2	110	*
W42	G25.4-0.2	13.4	82	Blum et al. (2000), *
W43	G30.8-0.0	7	107	Blum et al. (1999), *
W49	G43.2-0.0	13.8	172	Conti & Blum (2002 <i>a, b</i> ), *
W51	G49.x-0.3	6	154	Goldader & Wynn-Williams (1994)

<sup>a</sup> Original distance from Smith et al. (1978), using distance to the Galactic center (GC) of 10 kpc. Distance and luminosity should be revised for a distance to the GC of 8 kpc (Reid 1993). New near infrared spectroscopic distances have been determined for M17, W43, W42, and W31; see text. A “:” indicates the far radio recombination line distance.

<sup>b</sup> Reference for near infrared observations. A “\*” indicates *JHK* imaging and/or spectroscopy exist from the present survey.

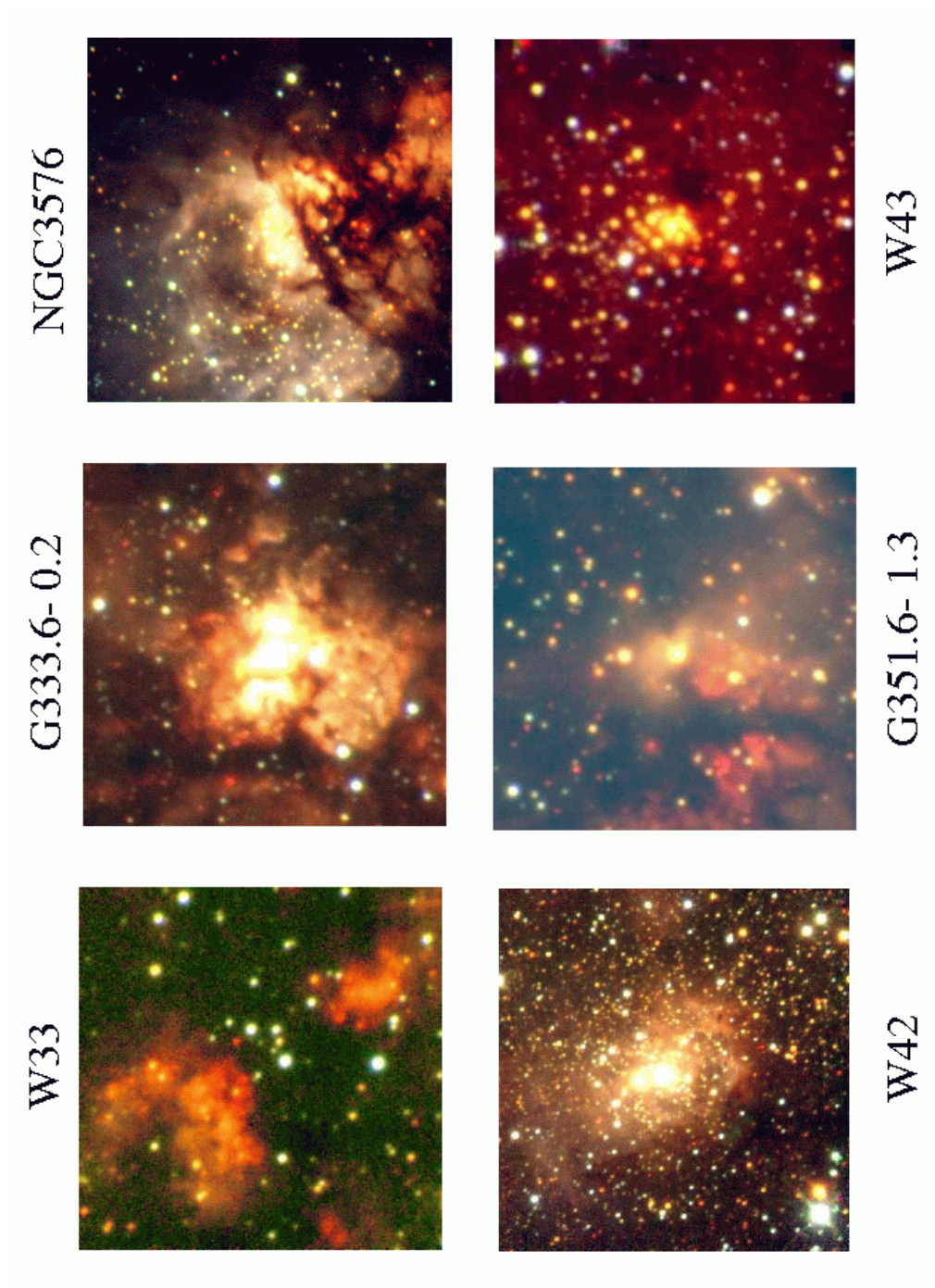


Figure 1. A representative sample of  $JHK$  three-color images for survey clusters. The clusters can serve as a loose “evolutionary” sequence. The OB stars in W33 and G333.6-0.2 are still highly veiled, while those in W43 have emerged and show normal infrared spectral types; see text.

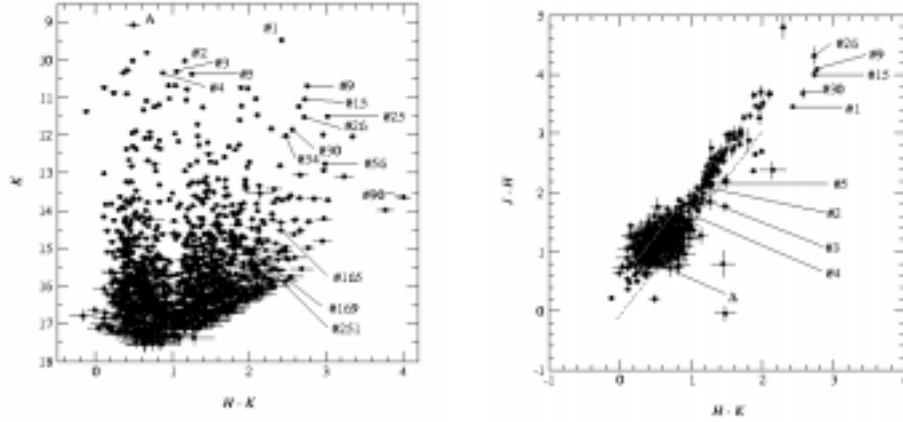


Figure 2.  $H - K$  color-magnitude diagram and  $J - H$  vs.  $H - K$  color-color plot for the W31 cluster and surrounding field. The stars labeled #2 – #5 are O stars. Stars labeled #1, 9, 15, 26, and 30 are massive young stellar object candidates;. The remaining labeled objects are candidate counterparts to 5 GHz radio sources.

and W31 have main sequence O stars (Blum et al. 2000, 2001) which are very young. It is clear that selecting GHII regions by their Lyman continuum output generally biases the survey to the youngest emergent clusters since the associated nebulosity has not yet been dispersed by the energetic winds and radiation pressure from the hot stars. This means that somewhat older, even luminous clusters could go undetected.

A typical color magnitude diagram (CMD) and color-color plot are shown in Figure 2. These particular diagrams are for W31, but the basic features are common to the GHII region clusters in general. The main features are a foreground sequence at bluer  $H - K$ , a cluster sequence to the red, strong differential reddening which produces a larger scatter in  $H - K$  than the typical photometric uncertainty, and a sequence of stars with an indicated excess of emission in  $H - K$  in the color-color plot. These objects lie to the red in this diagram compared to stars whose colors are consistent with “normal” stellar colors seen through a column of dust (some combination of interstellar and local).

The presence of these “excess” objects is particularly exciting because it allows us to investigate aspects of the massive star birth process; their presence also strongly suggests that revealed O stars are on, or nearly on the zero age main-sequence (ZAMS, Hanson et al. 1997, Blum et al. 2000, 2001). For all the clusters associated with GHII regions in Table 1 for which a  $J - H$  vs.  $H - K$  diagram exists and for which some massive stars are conclusively identified by spectroscopic means, there exist young (e.g. UCHII) or pre main sequence objects, or both. It appears that the hottest O stars in M17 (Hanson et al. 1997) have blown away their natal material, while the less massive later O and B stars show clear disk signatures. These two groups are spatially segregated in M 17. Are the early O stars more efficient at removing their circumstellar material, or

do the two groups represent sequential star formation? W31 has a YSO which is brighter than the early O stars. Its spectrum exhibits permitted Fe II emission which Blum et al. (2001) take as evidence of a dense circumstellar flow or disk. Accounting for the larger circumstellar extinction and excess emission for this star, Blum et al. show (assuming the excess arises in a disk geometry) that it is most likely consistent with a late type O or early B star. This object is also associated with an UCHII radio source (Ghosh et al. 1989). The Lyman continuum output derived from the radio emission is consistent with the late O early B classification. Thus there is very strong evidence that some massive stars do form by processes which include a disk accretion phase.

However, no mid to early O star (i.e. one of the most massive type) has been found in any of the youngest clusters which shows evidence of a circumstellar disk. All such stars have formed recently in the presence of somewhat lower mass OB stars, some of which show unmistakable signs of disks. It is possible that the earliest stars are simply more efficient in removing their circumstellar material, and the disk phase is thus shorter. On the other hand, if the timescale for formation of the massive stars is similar to that for the lower mass stars as has been recently suggested (within 10%, Behrend & Maeder 2001) and these stars have formed at the same time, then the observations might suggest that the most massive stars do not form with associated disks.

The hot star spectra obtained in these young clusters are not just useful for studying the star birth process. With suitable calibrations, they can be used to determine spectrophotometric distances to the GHII regions effectively probing Galactic structure. The details of our technique are given in Blum et al. (2001). Briefly, the infrared spectra are used to determine an associated spectral type and absolute magnitude. The apparent brightness and extinction are known from the *JHK* photometry and a distance is determined from the intrinsic and observed brightness. The largest uncertainty is due to the intrinsic scatter in the known brightnesses of the O stars (Vacca, Shull, & Garmany 1996) and the unknown age of the O stars. The former can be improved upon by maximizing the number of stars in a cluster with individual distances determined, the latter by observing fainter B stars which can't have evolved off the main sequence appreciably.

### 3. The Galactic Center

Forrest et al. (1987) and Allen et al. (1990) discovered that a very young stellar component ( $< 10$  Myr) exists in the Galactic center (GC) by associating near infrared emission lines which arise in the energetic winds of massive stars with compact (stellar) sources in the central pc. Later, Krabbe et al. (1991) established that a cluster of such evolved stars was located in the GC which represented the most recent episode of star formation there. Since then, a host of additional studies have refined the observed properties of the emission-line stars (Najarro et al. 1994, Libonate et al. 1995, Blum et al. 1995*a,b*, Krabbe et al. 1995, Tamblyn et al. 1996, Najarro et al. 1997, Paumard et al. 2001). However, questions still remain about whether the emission-line stars represent normal stellar evolution or the result of environmental effects in the extreme GC

environment (e.g. collisional mergers). See Tamblyn et al. (1996) and Najarro et al. (1997) for differing points of view.

For many years, GC investigators have sought evidence of the lower-mass stars (main-sequence and giants) which must have accompanied the emission-line stars at the time of formation if the latter indeed sprang from normal stellar progenitors. However, the combined effects of crowding and differential extinction have rendered searches for this component fruitless, until recently. Progress has been made on this issue by combining the Gemini adaptive optics image quality with a set of very closely spaced narrow filters. Using data from filters centered on the CO band head at  $2.3\ \mu\text{m}$  and a nearby continuum position ( $2.26\ \mu\text{m}$ ), taken as part of the Gemini demo science program, we have identified the lower-mass sequence of stars associated with the cluster of massive emission-line stars. Figure 3 shows the CO index ( $\text{Kcont flux} - \text{CO flux} / \text{Kcont flux}$ ) for the central  $20''$ , which includes the emission-line star cluster (IRS 16, Krabbe et al. 1991). Two sequences are present. The older population has steadily increasing CO index (more positive index in the Figure for stars with brighter Kcont magnitudes; e.g, Kleinmann & Hall 1986, Blum et al. 1996, Ramírez et al. 1998) which is expected for AGB stars and M supergiants, while the young sequence has CO indices which reflect the (essentially constant) continuum slope of the reddened ( $A_K \sim 3$ ) Rayleigh-Jeans tail for hot stars. Figure 4 shows the same index, but for stars in a field  $20''$  N of the central field, clearly indicating the young sequence is highly concentrated in the central region. The brightest members of the young sequence include the IRS 16 stars.

By using observations in an offset field such as shown in Figure 4, a statistical estimate of the total number of stars associated with the young sequence can be made in the central pc. However, spectroscopy is still required to pin down the true nature of the young stars. Detection of normal photospheric features in the  $K$ -band would unambiguously show the young emission-line stars in the GC to be derived from more or less normal stellar progenitors. An independent estimate of the overall mass scale for the young stars would also follow. Models have been computed for several of the emission-line stars (Najarro et al. 1997) allowing them to be placed in the HR diagram, but the results may depend on the specific physics included (e.g, so far no line-blanketed models have been computed). In any case, estimating masses from the spectral types of stars based on photospheric features is more straightforward than interpreting the spectra of evolved emission-line objects. The young stellar sequence indicated in Figure 4 is not confined to the so-called SgrA\*(IR) cluster immediately surrounding the black hole at the GC (Ghez et al. 1998, Genzel et al. 2000), but includes at least some of those stars. The SgrA\*(IR) cluster stars observed spectroscopically do not show strong CO absorption (Eckart et al. 1999, Figer et al. 2000).

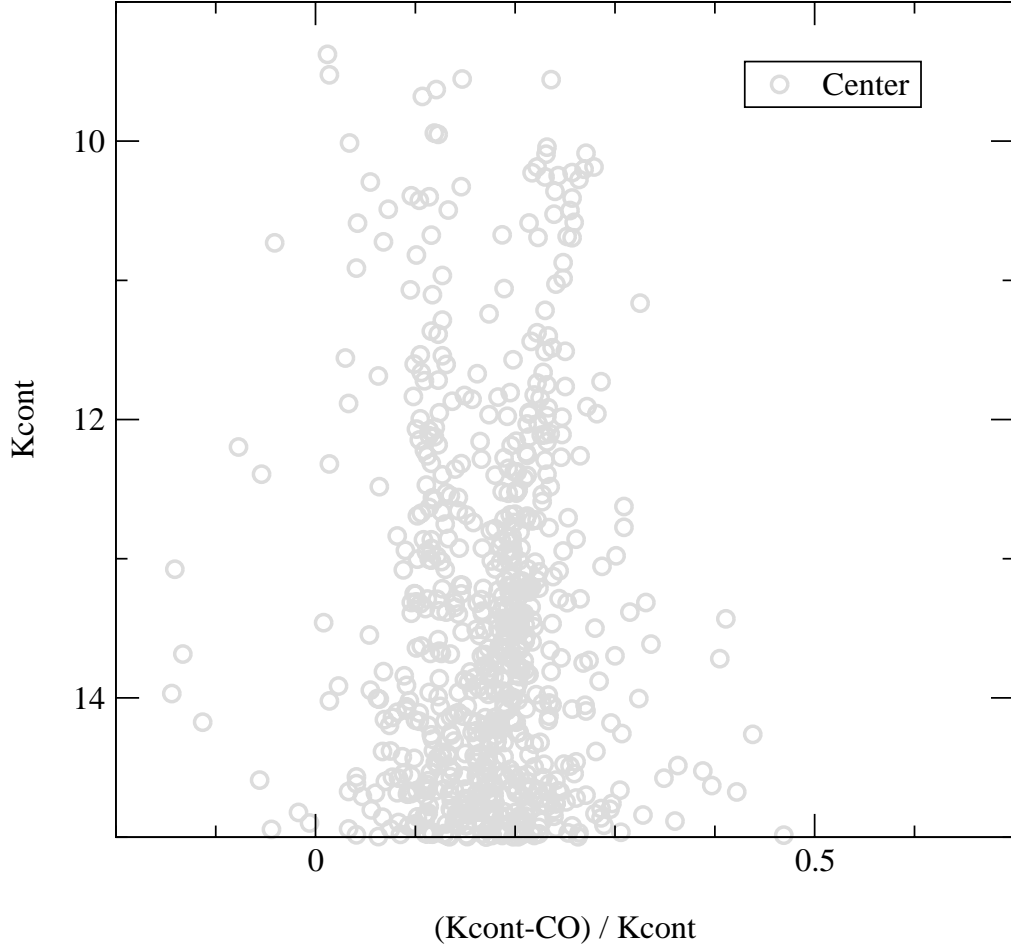


Figure 3. K<sub>cont</sub> magnitude vs. the CO index (K<sub>cont</sub> flux – CO flux / K<sub>cont</sub> flux) for the central 20'' of the Galactic center (*open circles*). The sequence to the left, with weak CO indices, represents the OB stars associated with the most recent burst of star formation in the GC. The sequence to the right is M supergiants and older AGB stars, which have strong CO indices that increase for brighter K<sub>cont</sub> magnitudes.



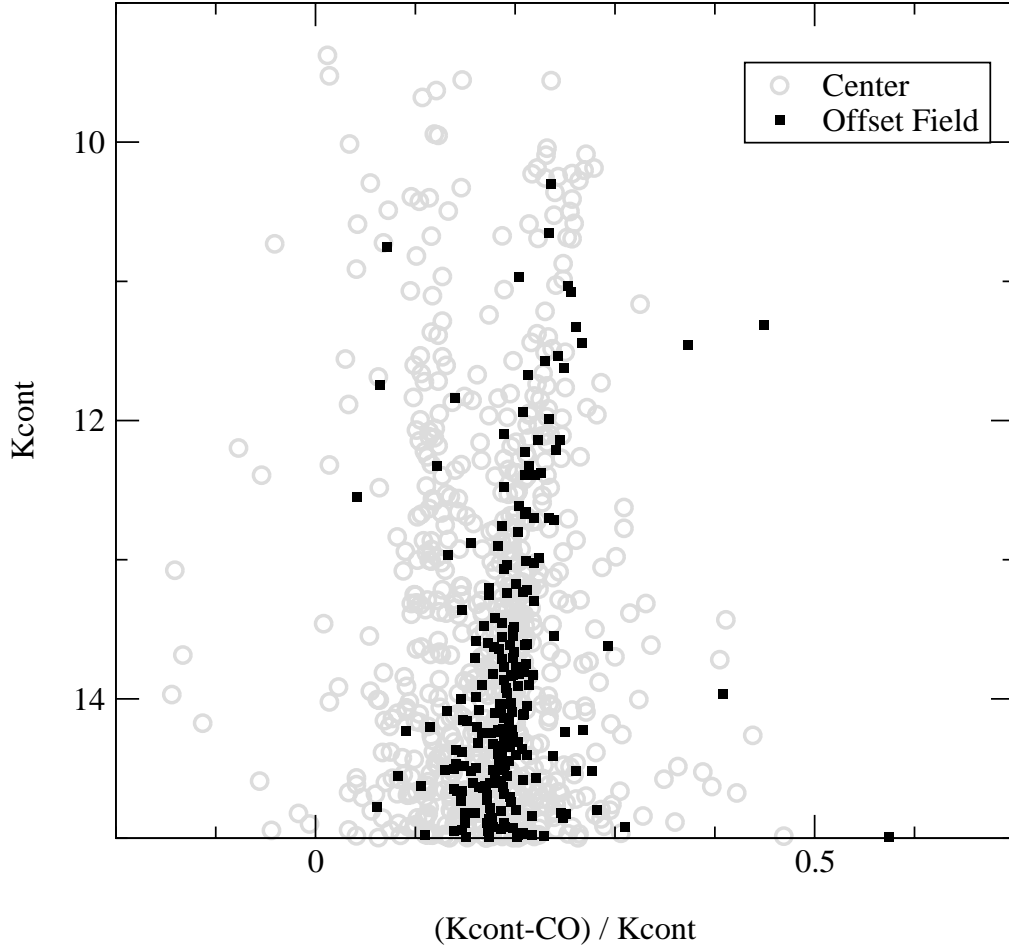


Figure 4. Overlay of the GC CO indices with the CO indices of a control field  $20''$  N of the GC (*filled squares*). The control field stars fall along the same CO index sequence as the older population in the GC with strong CO indices, but there are few stars on the young sequence which is highly concentrated to the GC field.

#### 4. The Arches Cluster and the IMF

The Arches star cluster was discovered recently in limited near infrared surveys (Nagata et al. 1995; Cotera et al. 1996) 30 pc in projection from the Galactic center (GC). Soon after, it was recognized that the Arches is one of the most massive young star clusters in the Milky Way and Magellanic Clouds (Serabyn et al. 1998). Serabyn et al. estimated that the Arches contains some 100+ OB stars in a projected area of about 0.5 pc. The Arches had lain hidden for so long only because it was obscured by 30 magnitudes of intervening visual extinction. The Arches is one of the three nearest young, massive star clusters which can be studied at high angular resolution (along with NGC3603 in the Galaxy, and R136 in the Large Magellanic Cloud-LMC). It is the only nearby cluster which is also found in a dense circumnuclear environment. Detailed studies of such nearby mini-starbursts are essential to establish the stellar mass function which is produced by this prolific mode of star formation.

Following the work of Serabyn et al., Figer et al. (1999) used HST/NICMOS images to show that the Arches is similar in total mass to the mini-starburst cluster R136 in the LMC ( $\gtrsim 10^4 M_{\odot}$ ) and perhaps 10 times as dense ( $3 \times 10^5 M_{\odot} \text{ pc}^{-3}$ ). More importantly, Figer et al. (1999) estimated the mass function in the Arches to be significantly flatter than a normal Salpeter (1955) power-law. Figer et al. find the power-law slope for the Arches to be  $\Gamma = -0.7$  compared to  $-1.35$  for Salpeter. This is in stark contrast to R136 (Massey & Hunter 1998) and the OB associations in the Milky Way (Massey et al. 1995) which exhibit Salpeter-like slopes,  $\Gamma = -1.0$  to  $-1.4$ .

Figer et al. (1999) argued that the flat mass function in the Arches was to be expected because the preconditions (namely high turbulent velocity and magnetic field strength) in GC star-forming clouds would naturally tend to produce more massive stars – a higher Jeans mass would be required to overcome these forces which oppose gravitational collapse (see Morris and Serabyn 1996). But Portegies Zwart et al. (2001) have computed dynamical evolution models of the Arches against the background potential of the GC. They claim the Arches mass function may only appear flat because dynamical segregation has removed lower mass stars to larger radii than were observed by Figer et al. (1999). The models can produce a flat mass function in the core of the Arches cluster, similar to the observed mass function, but a mass function for the entire cluster that is normal. It is only the observational constraint of having excluded the outer regions of the cluster which leads to the observed mass function being anomalously flat.

We have used the Gemini Demo science observations to explore the mass function in the core of the Arches. These Gemini adaptive optics observations have better image quality and thus go deeper in the core of the Arches than previous HST data. Like the HST data, the Gemini data indicate a flatter mass function than the Salpeter (1955) case and that in R136 (Massey & Hunter 1998). However it is intermediate,  $\Gamma \approx -0.9$ , and not too different from the OB associations in the Milky Way (Massey et al. 1995), but see Eisenhauer et al. (1998) for the case of NGC3603 (who give an upper limit to the slope,  $\Gamma \leq -0.73$ ). Figure 5 shows the mass function derived from these  $K'$  images. The slope can change by  $\sim \pm 5$ –10 % for different isochrones used to transfer the

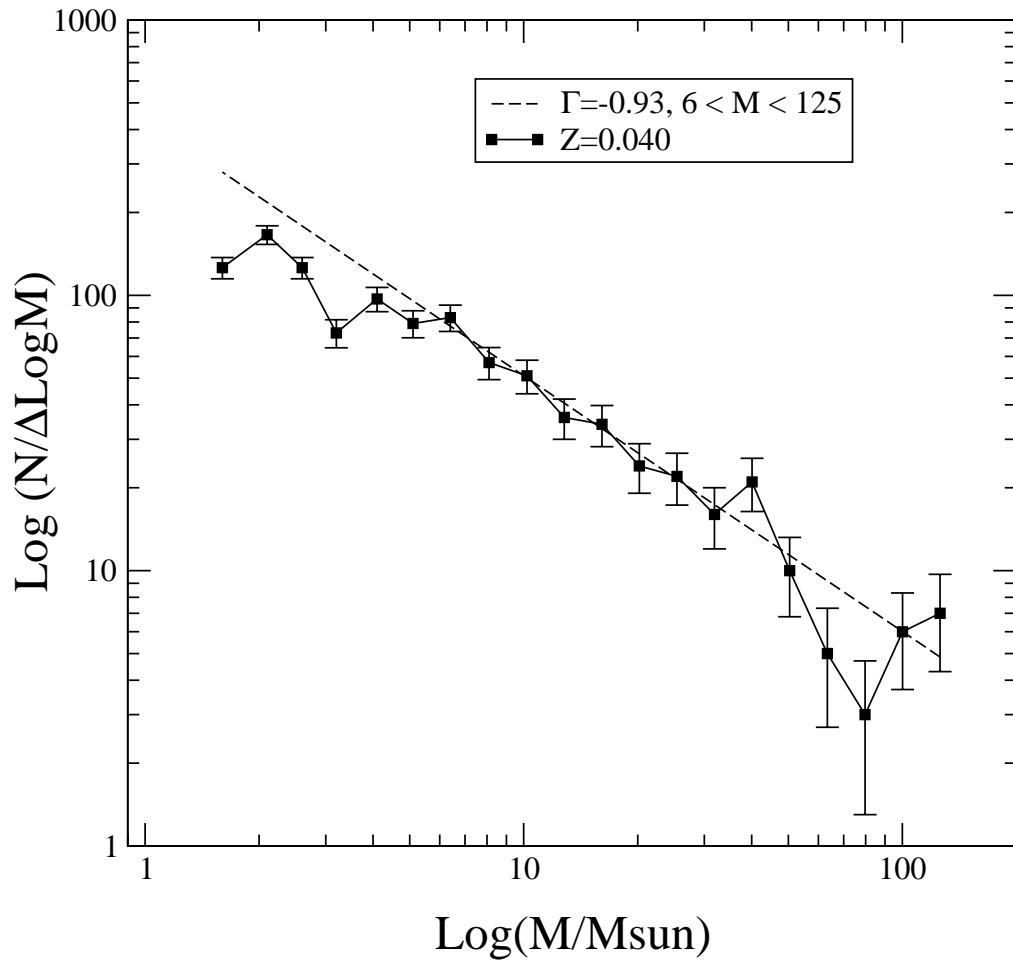


Figure 5. Mass function in the Arches cluster derived from Gemini North Demo Science Hokupa'a+QUIRC  $K'$  images. The slope is not as flat as the HST images, but still flatter than Salpeter (1955). The slope is uncertain mainly due to the choice of isochrones ( $\pm 5\text{-}10\%$ ) used to transform  $K'$  to mass.

$K$  magnitudes to mass (Schaller et al. 1992, Meynet et al. 1994). The result is preliminary; there are still significant areas of uncertainty. For example, the background stellar population (here estimated from the HST/NICMOS data of Figer et al. 1999) is rather uncertain. Binary fraction has not been included, and the stellar models do not include the effects of rotation which are probably significant (Maeder & Meynet 2000, Meynet & Maeder 2000). Cotera et al. (2001) will explore these issues in more depth. Furthermore, additional observations are needed to explore the issue of dynamical segregation.

In the meantime, a comparison to preliminary measurements of the mass function in the GHII region clusters places the Arches firmly at the flat end of the distribution. The values of  $\Gamma$  for W31, NGC3576, and W42 are  $-1.3$ ,  $-1.4$ , and  $-1.5$ , respectively. These are the youngest clusters in our sample with identified young stellar objects or UCHII regions. The young age and fact that these clusters are far from the powerful influence of the inner Galactic potential suggests they are ideal for measuring the initial mass function in massive star, star clusters.

## 5. Summary

The observational basis for the emergent star birth properties of massive stars in clusters is growing rapidly through the application of near infrared techniques to individual clusters in the Galaxy. Clusters with a few to more than 100 OB stars have been identified and detailed spectra obtained for the brighter members. Progress is being made on measuring the mass function produced by these “mini-starburst” episodes. The clusters located in the more extreme region of the Galactic center maybe the most massive and dense clusters in the Galaxy. However, the clusters seen toward the GHII regions may be the most ideal for establishing the mass function since they are younger and less affected by the Galactic center potential.

Young stellar objects (YSO) are found in essentially all these young massive star forming regions. The analogous high mass objects to the lower mass YSOs are ultra-compact H II regions: OB stars which are burning hydrogen, unlike low mass YSOs, but which have not yet revealed their photospheres. A number of these, as well as more revealed OB stars, show evidence for circumstellar disks. Thus, at least some massive stars appear to form through a process which includes a disk accretion phase. However, the most massive O stars revealed in the young clusters do not show evidence for disks. The disk phase may be too short to observe in the most massive stars, or perhaps it does not occur.

For the first time, a clear sequence of lower mass stars has been associated with the Galactic center He I emission-line stars. This sequence is evident in high angular resolution adaptive optics narrow-band images of the central pc. The sequence is spatially extended ( $\sim 20''$ ) compared to the SgrA\*(IR) cluster of stars immediately surrounding the nuclear black hole.

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